Second International Symposium on Marine Propulsors
smp'11, Hamburg, Germany, June 2011

A Fast Quasi-Steady Procedure for Estimating the Unsteady Forces and Moments on A Marine Propeller Behind a Hull

Robert F. Roddy

Naval Surface Warfare Center Carderock Division (DTMB), Bethesda, Maryland, USA

ABSTRACT

The development and implementation of a semi-empirical method to estimate the unsteady forces and moments on an open marine propeller mounted behind a hull are discussed. The method relies upon a quasi-steady approach that allows the code to rapidly estimate the forces and moments for a wide variety of propellers. Unlike most other quasi-steady methods that use a point velocity or a velocity integrated over a line, this method uses a technique to weight the chord-wise velocity distribution to obtain an equivalent velocity for each radius; then to integrate those velocities across the span of the blade. An empirical correction was also developed that allows this method to be used with propellers in inclined flow. It is this weighted integral that allows this method to perform as well as it does. In general, it works better than the Tsakonas method (1974) of Stevens Institute. However, it is not better than the Kerwin and Lee (1978) method of MIT when an expert runs the MIT program. The required input is easy to prepare and requires three types of normally available data: basic propeller geometry; propeller open water curve tabulation; and, wake survey results. The available unsteady experimental data is decomposed into a small subset used to develop the weighting, and the remainder used to validate the model. This represents a valuable departure from other empirical approaches that require most of the data for development. The results from this program, compared to experimental results and other prediction methods, are shown.

Keywords

Propeller, Unsteady Force, Empirical, Quasi-Steady

NOMENCLATURE

AR	Aspect Ratio
BR-Q	Blade Rate Unsteady Torque
BR-T	Blade Rate Unsteady Thrust
c	Chord Length of Airfoil
D	Propeller Diameter
EAR	Propeller Expanded Area Ratio
Exp	Experimental Result
J	Propeller Advance Coefficient [V/(nD)]
K_Q	Propeller Torque Coefficient $[Q/(\rho n^2 D^5)]$
K_T	Propeller Thrust Coefficient $[T/(\rho n^2 D^4)]$
L	Airfoil Lift
MIT	Massachusetts Institute of Technology
n	Propeller Revolutions per Second
PPAPPF	Unsteady Propeller Prediction Program from SIT
PPDIREC	Unsteady Propeller Prediction Program from SIT
PUF	Unsteady Propeller Prediction Program from MIT
PUF2d	Unsteady Propeller Prediction Program from MIT
Q	Propeller Torque
QS	Quasi-Steady Propeller Prediction
R_n	Reynolds Number
SIT	Stevens Institute of Technology
T	Propeller Thrust
U	Velocity of Flight for Figure 3
V	Velocity or Transverse Velocity for Figure 3
V_r/V	Radial Velocity Component of Propeller Wake
V_t/V	Tangential Velocity Component of Propeller Wake
V_x/V	Longitudinal Velocity Component of Propeller Wake
Z	Number of Blades on a Propeller
ϕ_n	Phase Angle
η_o	Propeller Open Water Efficiency
κ_e	Effective Reduced Frequency
π	PI = 3.14159
θ	Angular Position
ρ	Fluid Density
Subscripts	
des	Design
i	Instantaneous
us	Unsteady
Over-Strikes	
~	Unsteady
—	Average

1 INTRODUCTION

In the last 40 years there has been an interest in alternating propeller shaft forces, which are induced by

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUN 2011**	2. REPORT TYPE	3. DATES COVERED **00-00-2011 to 00-00-2011**

4. TITLE AND SUBTITLE **A Fast Quasi-Steady Procedure For Estimating The Unsteady Forces And Moments On A Marine Propeller Behind A Hull**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Surface Warfare Center Carderock Division (DTMB),Bethesda,MD,20817**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Second International Symposium on Marine Propulsors smp-11, Hamburg, Germany, June 2011

14. ABSTRACT
The development and implementation of a semi-empirical method to estimate the unsteady forces and moments on an open marine propeller mounted behind a hull are discussed. The method relies upon a quasi-steady approach that allows the code to rapidly estimate the forces and moments for a wide variety of propellers. Unlike most other quasi-steady methods that use a point velocity or a velocity integrated over a line, this method uses a technique to weight the chord-wise velocity distribution to obtain an equivalent velocity for each radius; then to integrate those velocities across the span of the blade. An empirical correction was also developed that allows this method to be used with propellers in inclined flow. It is this weighted integral that allows this method to perform as well as it does. In general, it works better than the Tsakonas method (1974) of Stevens Institute. However, it is not better than the Kerwin and Lee (1978) method of MIT when an expert runs the MIT program. The required input is easy to prepare and requires three types of normally available data: basic propeller geometry; propeller open water curve tabulation; and, wake survey results. The available unsteady experimental data is decomposed into a small subset used to develop the weighting, and the remainder used to validate the model. This represents a valuable departure from other empirical approaches that require most of the data for development. The results from this program, compared to experimental results and other prediction methods, are shown.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**12**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

non-uniform flow into the propeller disc. This is principally due to the fact that as the newer ships have had larger installed powers and, at times, higher design speeds, the problem of propeller induced vibration in the ship's structure has become a major concern; a concern not only with the structural integrity but also with crew comfort and, for military ships, with the ability to run quietly. It soon became apparent that it was necessary to develop some method to reliably predict the unsteady forces and moments that are transmitted through the propeller shafting. Not only was it necessary to be able to predict these forces, it was essential to develop an approach to design propellers so as to minimize these forces.

Several different techniques for predicting the unsteady forces on a propeller have been developed. These can be roughly grouped into four categories: (1) Quasi-steady methods; (2) two-dimensional unsteady methods; (3) a combination of quasi-steady and two-dimensional unsteady methods; and (4) three-dimensional unsteady methods. Good analyses and comparisons of these different methods are in publications by Boswell (1967), Jessup (1990), and Fuhs (2005).

Comparing the experimental results and analytical predictions from these references and other results (published and unpublished), the analytical methods discussed by Boswell (1967) were either not sufficiently accurate, were cumbersome and expensive to use, or both. In this paper, an empirical procedure for predicting the unsteady forces on a propeller is developed that is simple enough to be easily understood, sufficiently fast to be an economical engineering tool, and produces predictions that compare favorably with experimental results. It is basically a quasi-steady procedure where the method of calculating the instantaneous velocities over the surface of the propeller blades has been empirically determined.

This paper first presents a brief overview of the calculation technique, and then discusses the derivation of the empirical calculation procedure and the comparison with experimental results and other predictions; after which it provides a step-by-step description of the calculation method, and finally, it offers a brief discussion of the computer implementation of the procedure.

2 DEVELOPMENT OF AN UNSTEADY CALCULATION PROCEDURE FOR MARINE PROPELLERS

2.1 Background

In the past some researchers have broken the calculation of the fluctuating forces into two parts; one, the quasi-steady part, and two, the truly unsteady part. The procedure utilized in this paper is basically a quasi-steady technique for calculating the fluctuating forces on a marine propeller. A quasi-steady theory assumes that the instantaneous forces on an airfoil or propeller blade may be determined from the instantaneous values of inflow velocity to the foil. Included in this paper is a rationale for possibly accounting for some of the unsteady effects that are not accounted for by the usual quasi-steady methods. The unsteadiness results in a time dependent variation in the vorticity distribution in the downstream wake caused by the constantly varying velocity distributions on the foil. These effects prevent the full steady state lift predicted by the quasi-steady assumption from being produced.

As applied to a marine propeller, the unsteady thrusts and torques are determined by examining the forces on only one blade of the propeller at a time where the blade forces are determined for a number of discrete positions throughout the propeller rotation. At each blade position a local inflow velocity to the blade is determined from the spatially non-uniform wake conditions in the vicinity of the blade. This velocity is then used to determine the instantaneous thrust and torque from the open water performance characteristics. A typical example of a spatially non-uniform wake and a set of open water performance curves are shown in Figures 1 and 2. An implicit assumption made here is that the unsteadiness does not cause the mutual interference between adjacent propeller blades to change significantly from the steady state condition. The total force is calculated by summing the single blade forces over the number of blades, taking into account the proper phase angle between the blades.

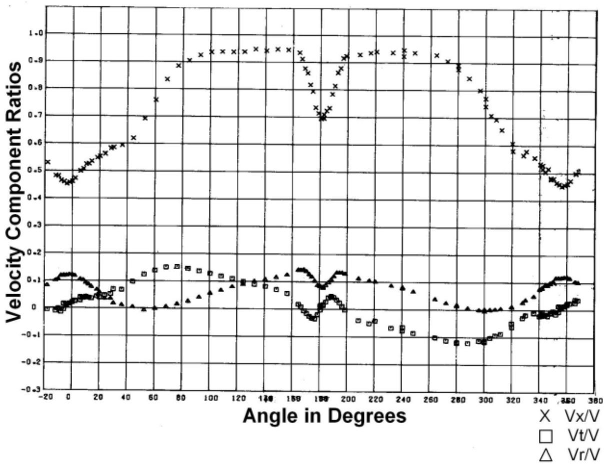

Figure 1 – Example of a Spatially Non-Uniform Wake on a Single Screw Ship

In the previous paragraph it was not stated "how" the local velocity at the propeller blade was determined. Historically, quasi-steady methods such as McCarthy (1961) have determined the "effective inflow velocity" by arbitrarily using the velocity at a point, possibly the mid-chord point at the 0.7 radius or from an integration of several points radially along the reference or skew line. This, at best, can only represent the velocity on a line of encounter. The major improvement in the present method is that the effective inflow velocity is determined from a weighted integration of the velocities over the entire blade surface.

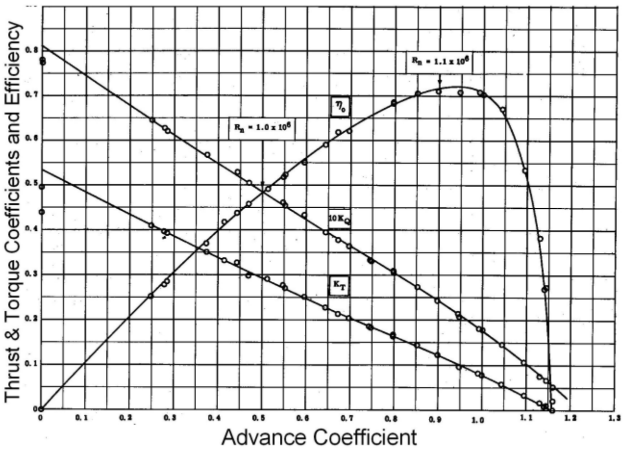

Figure 2 – Example of an Open Water Curve – Propeller Number 4118

It appears from existing data that the propeller blade forces are principally influenced by the flow conditions around the propeller leading edge area and that the effects of a changing inflow velocity on the blade forces diminish rapidly aft of this area; therefore, in calculating the unsteady forces, the inflow velocities around the leading edge will have to be weighted much more heavily than the velocities around the after part of a blade section.

This observation is supported by von Karman (1938), who shows the lift on an airfoil entering a sharp-edged vertical gust (reproduced here as Figure 3). In this figure, it can be seen that the slope of the lift curve is essentially infinite when the leading edge of the foil enters the sharp edged gust. In other words, the most dramatic change in the lift occurs when there is a change in the flow conditions at the leading edge.

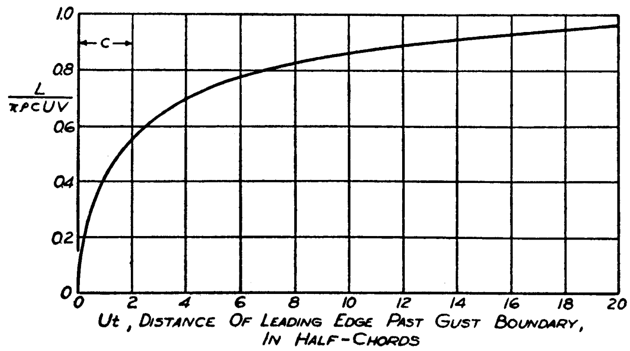

Figure 3 – The Lift on an Airfoil During and Following its Entrance into a Sharp-Edged Gust

How important is the unsteady portion of the fluctuating force solution and how does it vary for the typical range of marine propellers? For two-dimensional flows the unsteady part of the solution is very important, but as the flow becomes more "three-dimensional", the unsteady part of the solution becomes less important. In the limiting case, the unsteady part has no contribution at all. The flow around marine propellers lie somewhere between these two extremes, and it appears that, for engineering purposes, the unsteady part of the force solution may be considered not to vary significantly for the normal range of marine propellers.

The dependence of the degree of two- or three-dimensionality of the flow is illustrated in some results by Breslin (1970), based on Drischler (1956). Figure 4 shows the ratio of the unsteady lift to the quasi-steady lift response for rectangular foils in a sinusoidal gust of arbitrary amplitude. It is obvious from this figure that for foils in 2-dimensional flow the unsteady part of the solution is very important, but as the flow becomes more 3-dimensional the unsteady part of the solution becomes less and less important to the point, in the limiting case, where it has no contribution at all. If the quantities of reduced frequency, κ, and aspect ratio, AR in this figure, are converted to normal propeller parameters then an effective reduced frequency, κ_e, can be calculated for the propeller as:

$$\kappa_e = 2.74 \text{ (EAR)}, \qquad (1)$$

and the aspect ratio for the propeller blades will be:

$$\text{AR} = 0.64 \text{ (Z)/(EAR)} \qquad (2)$$

where "EAR" is the propeller expanded, area ratio and "Z" is the number of blades.
[Note: κ_e is a correction to that shown in Breslin (1970).]

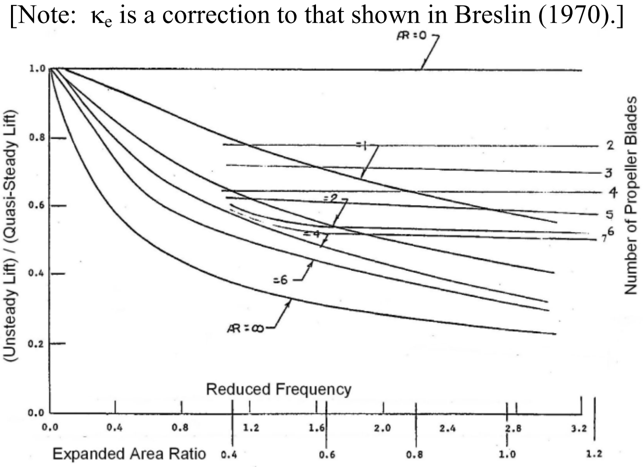

Figure 4 – Ratio of Unsteady to Quasi-steady Lift Response of Rectangular Foils to Sinusoidal Gust of Unit Amplitude in Terms of Propeller Parameters

When the normal range for propeller blade number, from 2 to 7, and the normal range for propeller blade area ratio, from 0.4 to 1.2, are used in the above equations and plotted in Figure 4, the results are quite interesting. In this figure, it should be noted, that for any given blade number, the ratio of unsteady to quasi-steady lift for the propeller is almost totally independent of the blade area ratio (for blade rate frequency). Also, for all blade numbers there is only about a 20 percent maximum error introduced when a mean value between the 2- and 7-bladed propellers is assumed (i.e., about that for a 4-bladed propeller). While the case shown in Figure 4 is a very special case, the trends shown here should be general in application. Also, the magnitudes shown can probably be considered as a "worst" case since propeller blades are not rectangular but rounded, and that would make the flow more 3-dimensional. A conclusion that may be drawn from the above discussion is that a single modeling for the unsteadiness, independent of reduced frequency, may be made and included within the velocity weighting function without introducing significant errors in the "overall" unsteady problem. The unsteady effects in an unsteady force calculation technique act as an effective "flow memory" which tends to cause a phase lag and a reduction in the peak-to-peak amplitude of the force response compared to a quasi-steady analysis. If the unsteady effects can, in any way, be included in an empirical method such as this, it should be exhibited in the character of the fall-off of the velocity weighting function in the after part of a propeller blade section.

2.2 Empirical Development

The specific nature of the velocity weighting for this calculation procedure was derived from the results of unsteady force measurements on only the 3-bladed propeller series of Boswell (1967). This reference contains one of the most complete parametric experimental programs investigating the unsteady forces on marine propellers. In this program, experiments were performed in both three- and four-cycle wake patterns (Figure 5), for three 3-bladed unskewed propellers of varying expanded area ratios and for one highly skewed 3-bladed propeller (Figure 6). The empirical derivation of the weighting function utilized only the experimental results for these four propellers operating at design K_T in the three cycle wake. Although it was felt, a priori, that the velocity weighting function would be similar in shape to the pressure distribution across a foil, a somewhat lengthy approach was taken that would both yield a satisfactory function and add to the understanding of how changes in the shape of the weighting function affect the unsteady force prediction. In this derivation, twelve different weighting functions were investigated.

The first weighting function was simply an averaging of the velocities over a 10-degree arc of the propeller disc. This was done at several radii and then a mean velocity was determined by integrating over the propeller radius. The area from which the velocities were taken would appear, visually, to be a very narrow "pie-shaped" segment of the propeller disc. The results produced with this velocity weighting function are similar to the traditional quasi-steady methods.

The first four of these functions tried were used to illustrate that the leading edge area was the critical region to be used in calculating the effective steady state velocity and that the contour of the leading edge of the propeller

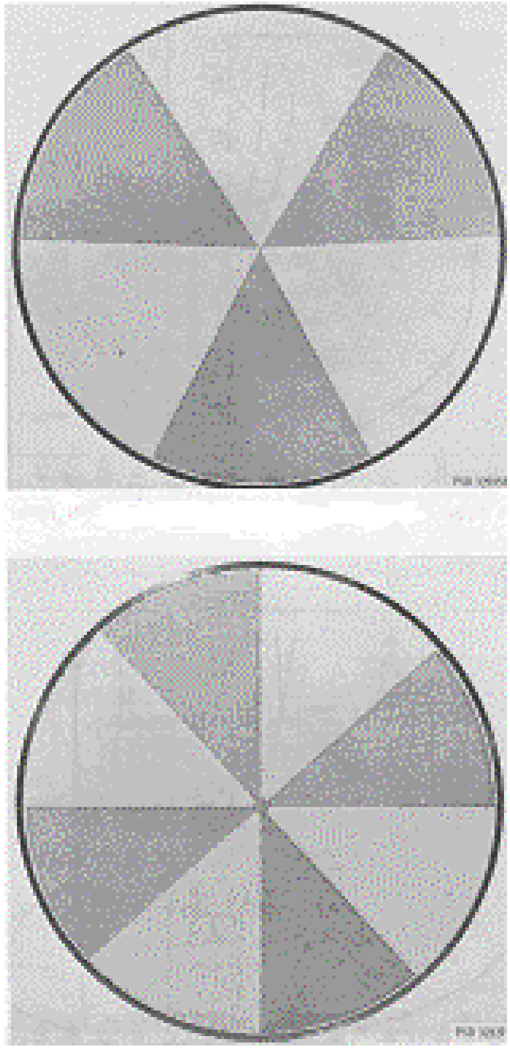

Figure 5 – Three-Cycle and Four-Cycle Wake Screens

Figure 6 – Three-Bladed Propeller Series

blades needed to be accurately represented. The fifth function, which evenly weighted the velocities over the entire blade, extended this proof and further illustrated the necessity of heavily weighting the leading edge area. Since the unsteadiness effects act as an effective "flow memory", it was thought that it might be necessary to include velocities downstream of the trailing edge of the blade. In the sixth through the ninth weighting functions, it was determined that not only was it not necessary to include these downstream velocities but even those velocities in the after part of the blade had to be progressively weighted less as the trailing edge was approached. The final nature of the falloff of the weighting function across the blade chord was determined in the tenth and eleventh weighting functions. Finally, in the twelfth weighting function a correction was added for propellers that have a mean projected blade width wider than the half cycle width of the wake (i.e., for a 3-cycle wake a half cycle is 60 degrees wide). Again, it should be stressed that this derivation was performed using only the design "K_T" unsteady measurements from the three unskewed propellers shown in Figure 6 and making occasional use of the measurements for the highly skewed propeller.

2.3 Comparison with Experimental Results

The results of this calculation technique, showing good agreement with the experimental data, are compared with other calculation techniques in Figures 7 and 8 for the 3-bladed unskewed propeller series of Boswell (1967). [Figures 7 and 8 are basically reproductions of Figures 27 and 28 of this reference.] (While the measurements illustrated in these figures are those that the present method's velocity weighting function was derived with, the comparison is generally valid as will be shown later in this section.) From these figures, the marked difference in results between an old quasi-steady method and the present one can easily be seen. In fact, the comparison between the measurements and the present method is better than that for the Tsakonas unsteady lifting surface methods investigated.

A final comparison with the Boswell measurements was made for the unsteady thrust and torque at multiples of blade rate frequencies. This was done as an additional check on the contention that the effects relative to the propeller blade aspect ratio and the reduced frequency tend to cancel. For a given propeller operating condition as higher multiples of blade rate forces are investigated, there are higher effective reduced frequencies that are associated with these forces. If there is not a cancellation of the effects of aspect ratio and reduced frequency, then the comparison of experimental data and predicted forces should progressively get worse as the multiples of blade rate frequencies get higher. The comparison of predictions and experimental data for the first through the fourth multiple of blade rate thrust and torque is presented in Table 1. Most of the predictions appear to be reasonable and the errors between experimental data and predictions are random instead of exhibiting any progressive behavior. While this does not prove that there is a cancellation of effects, it does support this contention.

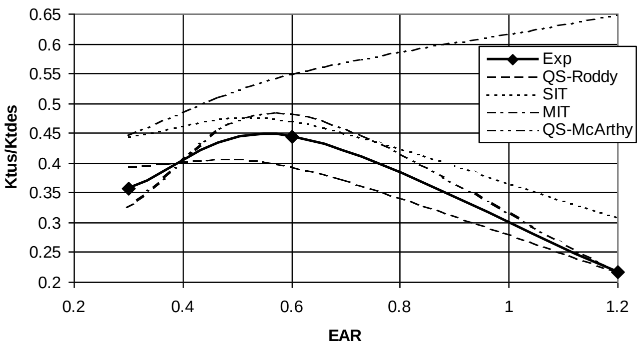

Figure 7 - Correlation of Blade Frequency Thrust Over Range of Expanded Area Ratios at Design K_T

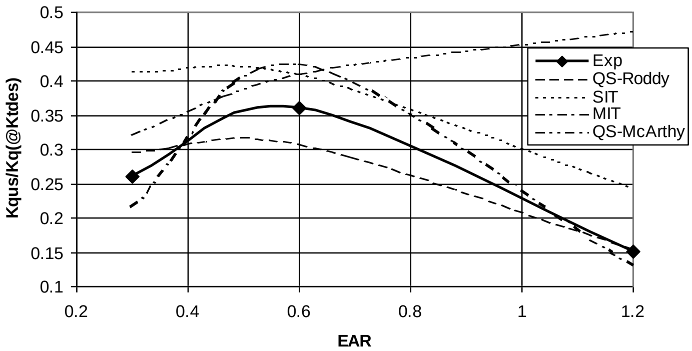

Figure 8 - Correlation of Blade Frequency Torque Over Range of Expanded Area Ratios at Design K_T

Table 1a – Comparison of Experimental Results and Predictions for Multiples of Blade Rate Frequencies

Miller-Boswell Unsteady Thrust Ratios				
EAR - - >	0.3	0.6	1.2	0.6 Skew
BR-T	Exp	Exp	Exp	Exp
1	0.358	0.445	0.218	0.051
2	0.036	0.030	0.030	0.011
3	0.038	0.026	0.062	0.004
4	0.022	0.020	0.003	0.022
BR-T	QS	QS	QS	QS
1	0.394	0.395	0.217	0.064
2	0.029	0.020	0.026	0.006
3	0.033	0.015	0.022	0.016
4	0.011	0.007	0.003	0.007
BR-T	PUF2d	PUF2d	PUF2d	PUF2d
1	0.325	0.482	0.217	0.139
2	0.025	0.041	0.019	0.004
3	0.022	0.015	0.006	0.007
4	0.004	0.004	0.001	0.002

Table 1b – Comparison of Experimental Results and Predictions for Multiples of Blade Rate Frequencies

Miller-Boswell Unsteady Torque Ratios				
EAR - - >	0.3	0.6	1.2	0.6 Skew
BR-Q	Exp	Exp	Exp	Exp
1	0.260	0.360	0.151	0.059
2	0.022	0.028	0.026	0.008
3	0.031	0.015	0.057	0.007
4	0.017	0.013	0.003	0.002
BR-Q	QS	QS	QS	QS
1	0.308	0.319	0.159	0.052
2	0.018	0.013	0.019	0.005
3	0.027	0.012	0.016	0.013
4	0.010	0.005	0.002	0.005
BR-Q	PUF2d	PUF2d	PUF2d	PUF2d
1	0.214	0.425	0.130	0.122
2	0.019	0.040	0.014	0.006
3	0.018	0.011	0.005	0.007
4	0.003	0.004	0.001	0.002

After the calculation method was developed, predictions were made for comparisons with most of the experimental data existing at the NSWCCD and with the results from two different three-dimensional unsteady lifting surface computational methods, PPAPPF & PPEXACT from SIT and PUF2-d from MIT. The results for the unsteady thrust and torque for these cases are presented in Table 2. From this table it can be seen that, on the average, the new procedure has smaller differences between experimental measurements and predictions than the Tsakonas three-dimensional unsteady lifting surface calculation procedures investigated, but not as good as the Kerwin Method of MIT. There are, however, two sets of data where this new calculation method does not produce results that are better than the Tsakonas 3-dimensional unsteady method. One set is shown in Table 2 as the "blade number variation"; the measurements were made in a wind tunnel and there may be a problem with the accuracies of the measurements. The other set is shown in Table 2 as the "skew series in a 5-cycle wake"; no explanation has been found as to why the empirical predictions do not produce better data than the Tsakonas 3-dimensional method for this set of water tunnel experiments, especially when it works well with the 5-cycle sheared wake. These two sets of data are included here, however, for the purposes of completeness and to alert the reader to places where this calculation technique has some shortcomings.

In addition to the above comparisons, a check was made to determine the ability of the new procedure to predict the unsteady forces in off design conditions. Predictions were performed for the 3-bladed Boswell series over a wide range of "J's" and compared with the experimental measurements (Figures 9 and 10).

The experimental comparisons presented in Table 2 and Figures 9 and 10 clearly illustrate that this empirical prediction technique is generally applicable for the combinations of ship wake and propellers that are normally found in the marine field.

3 FURTHER DEVELOPMENT

3.1 Propeller Side Forces and Bending Moments

Until this point only the unsteady thrust and torque have been predicted. We will now discuss the calculation of the shaft side forces and bending moments, and the blade bending moment at the blade root. To calculate these values, the following additional assumptions were made:

1) The side forces could be calculated by dividing the torque by the radial center of the torque. (i.e., the centroid of torque)
2) The bending moments could be calculated by multiplying the thrust by the radial center of thrust.
3) The blade bending moment could be calculated by combining the moments due to the trust and torque taken about the blade root.
4) The center of lift along a blade section is always at the 1/4 chord. (Boswell 1967)
5) The mean radial center of thrust and torque can be determined from standard lifting line techniques (generally around 0.66 of the propeller diameter).
6) The instantaneous centers of thrust and torque will vary inversely with the instantaneous centers of velocity. (i.e., the centroid of the velocity distribution).

The first five of these assumptions are rather trivial but the sixth one may not, at first, be obvious. The instantaneous thrusts and torques throughout the propeller rotation are calculated and known before the side force and bending moment calculations begin. Therefore, at any blade angular position the blade lift is already fixed. For a given lift, as the center of velocity moves toward the tip, the outer sections of the propeller will be experiencing a lower angle of attack and will therefore be producing less lift. This in turn means that the inner sections of the blade will have to carry a larger portion of the total lift; therefore, the radial center of lift varies inversely with the radial center of velocity. Theoretical calculations may prove that a simple inverse proportioning of the velocity centers is not strictly correct but physical reasoning shows that the trend is correct and in an empirical approach such as this, this is a reasonable approximation.

Table 2 - Comparison of Different Analytical Predictions with Experimental Results

Percent Errors in Unsteady Thrust and Torque for Training Data

Propeller & Conditions	Unsteady Thrust % Error				Unsteady Torque % Error			
	Roddy	PPAPPF	PPDIREC	PUF	Roddy	PPAPPF	PPDIREC	PUF
Boswell-Miller; Design J; EAR=0.3	10.1	10.2	24.2	-9.1	14.2	46.9	64.6	-17.5
Boswell-Miller; Design J; EAR=0.6	-11.6		5.9	8.4	-14.6	8.6	18.1	18.0
Boswell-Miller; Design J; EAR=1.2	-0.1		28.7	-0.5	2.8	10.6	64.3	-14.0
Boswell-Miller; Design J; EAR=0.6 (Skewed)	26.3	13.9			-18.3			
Average Percent Error for Training Data	**6.2**	**12.1**	**19.6**	**-0.4**	**-4.0**	**22.0**	**49.0**	**-4.5**

Percent Errors in Unsteady Thrust and Torque for Blind Prediction Data

Propeller & Conditions	Unsteady Thrust % Error				Unsteady Torque % Error			
	Roddy	PPAPPF	PPEXACT	PUF	Roddy	PPAPPF	PPEXACT	PUF
Model 5218; Prop 4013; Trim= 0 degrees	87.3	208.3	154.0	-56.7	-32.2	205.6	64.0	-96.3
Series 60; Wake Screen; Design J; Prop 4132	-3.6	30.6	4.0		1.0	96.1	19.0	
Series 60; Wake Screen; Design J; Prop 4143	-18.0	106.3	19.2		-31.6	103.5	-8.3	
Series 60; C_B=0.60; Run #7; Z=4	35.9	82.2			27.5	102.6		
Series 60; C_B=0.60; Run #46; Z=4	36.6	83.8			28.9	104.4		
Series 60; C_B=0.60; Run #63; Z=4	44.0	94.9			28.8	105.4		
Series 60; C_B=0.60; Run #38A; Z=6	105.0	144.4			95.0	156.9		
Blade Number Variation; Propeller Performance Estimated from B-Series; Z=3	-25.0	-9.9	-41.4					
Blade Number Variation; Propeller Performance Estimated from B-Series; Z=5	-33.9	-27.6	-51.2					
Blade Number Variation; Propeller Performance Estimated from B-Series; Z=7	53.6	33.9						
Skew Variation; 5 Cycle Sheared Wake; Z=5; Skew = 0 degrees	24.8	-69.5	-0.4		1.1	-93.4	20.1	
Skew Variation; 5 Cycle Sheared Wake; Z=5; Skew = 36 degrees	15.7	-76.6	2.1		-47.9	-95	11.8	
Skew Variation; 5 Cycle Sheared Wake; Z=5; Skew = 72 degrees	-8.3	-73.6	-6.7		-29.2	-94.3	-2.4	
Skew Variation; 5 Cycle Wake; Z=5; Skew = 0 degrees	-37.1	-11.2	-2.6		-38.9	2.5	7.8	
Skew Variation; 5 Cycle Wake; Z=5; Skew = 36 degrees	-43.9	-13.6	1.3		-46.6	-6.6	5.0	
Skew Variation; 5 Cycle Wake; Z=5; Skew = 72 degrees	-71.3	-17.9	-8.9		-70.0	-21.4	-13.7	
Skew Variation; 5 Cycle Wake; Z=5; Skew = 108 degrees	-47.6	30.3			-45.5	34.7		
FF-1088 Model Blade Force Measurements	54.6		5.9		154.8		100.0	
DD-963 Model Blade Force Measurements	29.2			72.6	-55.1			82.7
Average Percent Error for Predictions	**10.4**	**30.3**	**6.3**	**8.0**	**-3.7**	**42.9**	**20.3**	**-6.8**

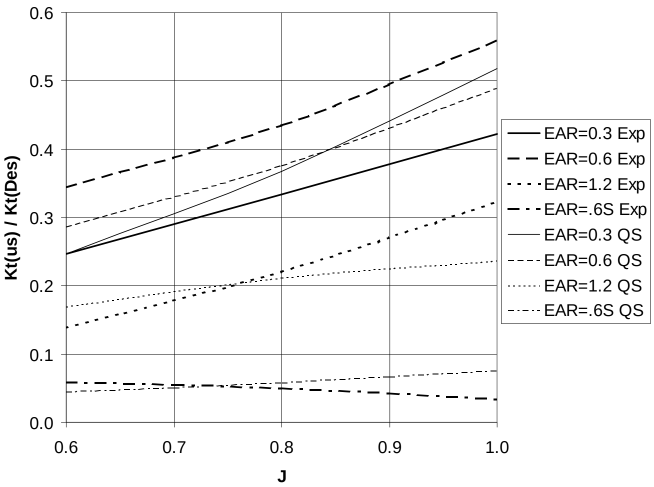

Figure 9 - Comparison of Experimental Blade-Frequency Thrust and Empirical Prediction in a 3-Cycle Wake

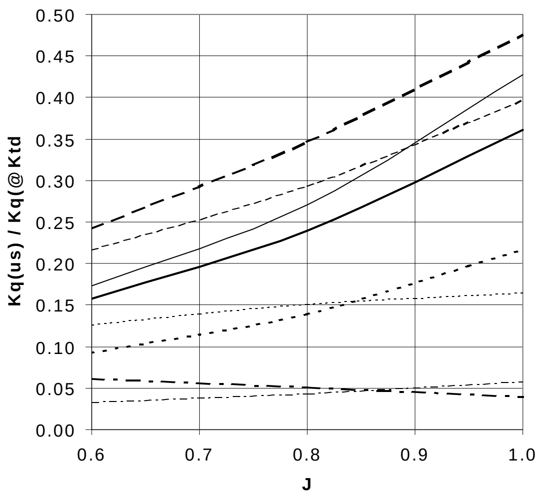

Figure 10 - Comparison of Experimental Blade-Frequency Thrust and Empirical Prediction in a 3-Cycle Wake

3.2 Calculation Procedure

The calculation method utilized here is divided into six major steps:

1) The preparation of the necessary input--ship/propeller operating condition, propeller geometry, wake harmonic analysis coefficients, and propeller open water characteristics.
2) The reconstruction of the longitudinal and tangential velocity component ratios from harmonic analysis coefficients throughout the propeller disc.
3) The calculation of the effective instantaneous wake for each blade position.
4) The calculation of the thrust and torque per blade at 36 discrete angular positions throughout the propeller disc.
5) The determination of the unsteady part of the thrust and torque.
6) The performance of harmonic analysis on the unsteady forces.

The specific information required for the first step is self-explanatory. For the ship/propeller operating conditions the <u>mean</u> values for the ship speed (V_S), Taylor wake fractions ($1-w_T$) and ($1-w_Q$), and the propeller thrust (T), torque (Q), and RPM are needed. The value for the water density (ρ) is also required. If the side forces and the bending moments are to be calculated, then two more quantities are also needed: the mean radial centers of thrust and torque. These values can be obtained from the results of propeller design lifting line calculations (or if there is no information available, past calculations indicate a good approximation is to assume 0.66). The use of the radial centers of thrust and torque has been discussed earlier.

In the second step of this procedure, the longitudinal and tangential velocity component ratios (V_x/V and V_t/V) are reconstructed from the harmonic analysis coefficients. These are in the form of:

$$\{V_x/V \text{ or } V_t/V\} = a_0 + \sum_{n=1}^{n=h} c_n * Sin(\theta + \phi_n) \qquad (3)$$

This is done at each of the radial positions, from hub to tip, for which there is information on propeller geometry. At each of these radial positions, the velocity component ratios are determined circumferentially throughout the propeller disc making modifications, where necessary, such that the angular position for the wake survey will agree with the angular position for the propeller. [The sign convention for the necessary modifications is valid for propellers on the centerline and on the port side of the centerline of the ship. For right hand propellers, the wake survey angular positions are complemented (i.e., 90 degrees becomes 270 degrees etc.) For left hand propellers, the angular positions are not changed but the sign of the tangential velocity components is reversed.] These velocities are subsequently used in determining the "effective" local velocities at each propeller blade position. The "effective wake" fractions for each blade position are determined in the third step.

The instantaneous thrusts and torques are determined from the propeller open water performance characteristics using the local velocities calculated in the previous step as:

$$T_i = K_{Ti}\rho n^2 D^4/Z \qquad Q_i = K_{Qi}\rho n^2 D^5/Z \qquad (4,5)$$

where

$$K_{Ti} = f_1(J_T) \qquad K_{Qi} = f_2(J_Q). \qquad (6,7)$$

The forces are then summed over the number of propeller blades and the mean forces are calculated ($\bar{T}$ and $\bar{Q}$). The mean forces are then compared with the values of thrust and torque specified in the first step (i.e., the steady state values, usually measured during model propulsion experiments). If the two values of thrust (and torque) are not the same (± 0.5 percent), a correction to the effective wake values is made using standard convergence techniques and the forces are recalculated. This iteration proceeds until the two values being compared are within tolerance. Since the amplitude of the velocity change is known from the third step of this procedure and since the slope of the open water characteristics is not linear, the amplitude of the unsteady forces will be incorrect unless the calculated mean force is correct.

In the fifth step, the unsteady part of the thrust (T) and torque (Q) is determined. The unsteady part of the force is simply calculated as the mean force minus the instantaneous force and is repeated for each of the propeller positions where the instantaneous force is determined (i.e., $\tilde{T} = \bar{T} - T_i$ and $\tilde{Q} = \bar{Q} - Q_i$) (8,9)

The propeller side forces and bending moments may be determined at this point in the calculation procedure if desired. These calculations are performed using the instantaneous values of thrust and torque determined in the fifth step.

To assist in the interpretation of the results of the previous steps, a harmonic analysis is performed on each set of unsteady forces. From these analyses, the blade rate and multiples of blade rate forces may be determined along with their associated phase angles. To summarize, at this point, the total instantaneous forces on the propeller have been calculated, the unsteady part of these forces has been determined, and a harmonic analysis of the unsteady forces yielded the integer multiples of the blade rate forces and their associated phase angles.

3.3 Correction for Propellers in Inclined Flow

The corrections made herein for propellers in inclined flow is an empirical correction made after observing the flow around a propeller operating in such conditions. Figure 11 shows an example of such flow conditions. From examining this figure it can be seen that the flow curls up very quickly aft of the propeller to resume its original flow direction. Since the flow downstream of a propeller in an open water test is always parallel to the propeller shaft line, the only possible modification seemed, to this author, to modify the flow ahead of the propeller by adjusting the tangential velocities (V_T/V) by an amount that appeared reasonable from the flow observations mentioned earlier. Since the flow curled up so quickly, a correction factor to the tangential velocities between 1.5 and 2.0 appeared reasonable. After a parametric investigation using the data from a single-screw and a twin-screw ship, both with inclined shafts supported by V-Struts, a correction factor of 1.8 was selected. Therefore, for propellers in inclined flow, the tangential velocities are multiplied by 1.8 and then used to determine the "effective wakes" for the propeller operation. Presented in Figure 12 are the test results of the unsteady blade thrust for a single blade of the single screw ship along with the predicted results with the tangential velocity correction.

4 USE OF CALCULATION PROCEDURE FOR PARAMETRIC INVESTIGATIONS

One of the uses for an unsteady force calculation procedure is the parametric investigation of skew to minimize certain bearing forces or moments for a particular ship design. This calculation technique lends itself very well to such investigations. In this section, it will be shown how this can be done efficiently and the results of a sample set of calculations will be presented and compared with those from a three-dimensional unsteady lifting surface method.

The principal reasons for the efficiency in performing investigations of the effects of the skew are that the calculation procedure only needs to determine the velocity components throughout the propeller disc once and that only one set of propeller performance characteristics need to be determined. In this procedure, after the velocity components are determined, they are stored and can be recalled at any time. It is also known that for marine propellers designed for a given set of operating conditions and only having different skews and skew distributions, the propeller performance for all the propellers around the design region should be about the same. This is not to imply that the performance is the same throughout the operating range because it is not and, in fact, at the two extremes of the first quadrant operating range there may be large differences.

Presented by Boswell and Cox (1974) is the design and evaluation of a highly skewed propeller for a cargo ship. In one phase of this design, "Calculations were performed using unsteady lifting surface theory…to minimize the pertinent components of the unsteady bearing forces." As part of the continued effort to design a propeller for this ship, a series of skew magnitudes and distributions were investigated and the unsteady loads for each were predicted using the method of Tsakonas. For some of the same designs the unsteady loads were also predicted using the empirical method herein described and were compared to those produced by the Tsakonas unsteady lifting surface method. A typical set of comparisons is presented in Figures 13 and 14. These figures are constructed to illustrate the trends of the predictions instead of the magnitudes of the forces and, as can be seen, there is excellent agreement in the alternating thrusts, but the agreement is not as good for the vertical side forces. As mentioned previously, the comparisons were better for the thrusts and torques than the side forces and the bending moments, and these results tend to bear out the earlier conclusions. Unfortunately, there are no experimental results to verify either calculation procedure.

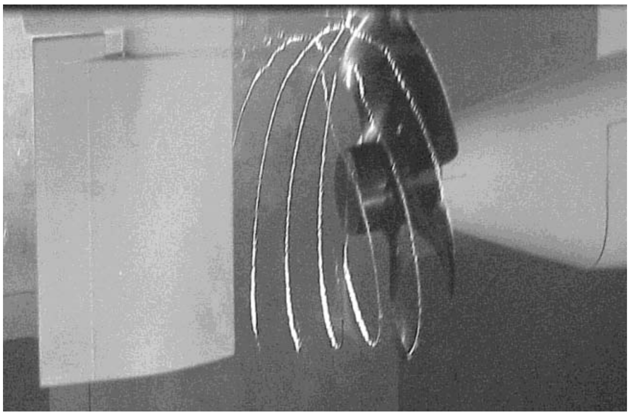

Figure 11 - Illustration of Propeller Operating in Inclined Flow

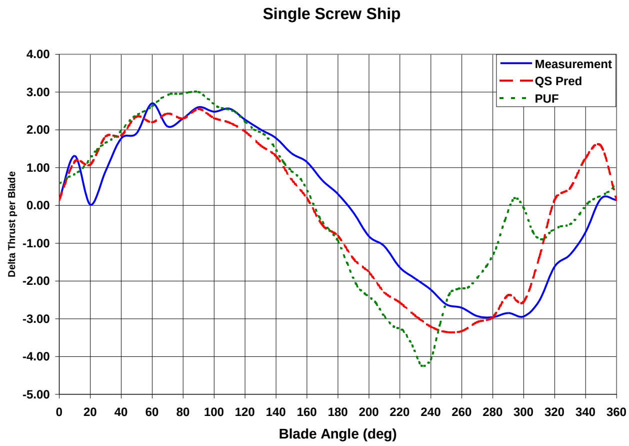

Figure 12 - Unsteady Thrust per Blade for a Single Screw Ship with a Propeller in Inclined Flow

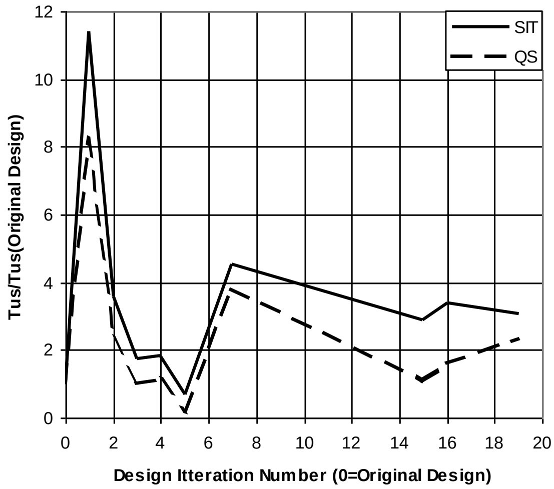

Figure 13 -Comparison of Unsteady Thrust Predictions for a Cargo Ship Using Empirical Method and Unsteady Lifting Surface Method

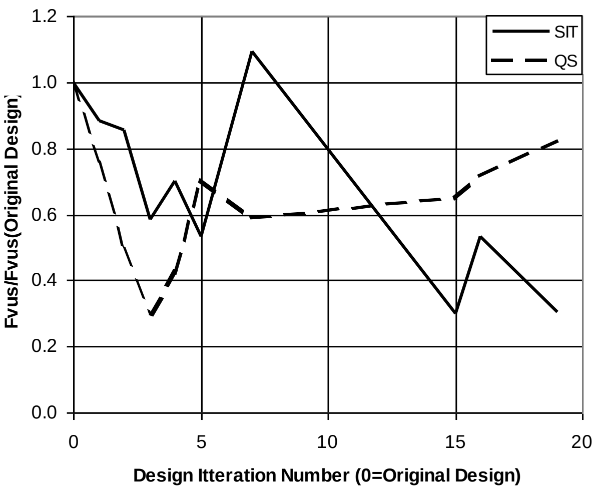

Figure 14 -Comparison of Unsteady Vertical Side Force Predictions for a Cargo Ship Using Empirical Method and Unsteady Lifting Surface Method

5 A COMPUTER PROGRAM FOR THE CALCULATION OF UNSTEADY LOADS FOR MARINE PROPELLERS

A computer program was developed, and is freely available from the author, for the calculation of the unsteady forces and moments produced by a marine propeller using the procedure developed earlier in this paper. Of paramount importance during the development of this program was the ability:

1) To have input to this program in a format that is familiar to most naval architects;
2) To have an easily understandable calculation method that could be modified with relative ease if calculation or output changes are desired;
3) To have a flexible procedure to meet as many needs of the naval architect as possible; and
4) To have a fast, economical program.

The output of this program includes a summary of all the input, important intermediate calculations, a tabulation of the unsteady loads, and a harmonic analysis of each of the unsteady loads for the same number of harmonics that were input with the wake information.

6 DISCUSSION AND CONCLUSIONS

In this paper, a procedure for the calculation of fluctuating loads on a marine propeller has been presented. The side forces and bending moments are not as accurate as those for the thrusts and torques; and by the very nature of this technique, field point pressures, forces and stresses at arbitrary points on a blade and other similar quantities cannot be determined by this method. It is because of just such restrictions that this empirical method is not meant to attempt to replace any of the theoretical lifting surface techniques. However this empirical technique is meant to be an economical engineering tool used where it is applicable. By comparison with experimental results the procedure is shown to be a good engineering tool with accuracies, on the average, surpassing the Tsakonas three-dimensional unsteady lifting surface methods for alternating thrust and torque; however, this procedure is not as good as the Kerwin method when the Kerwin method is run by an expert using an iterative method. However, if the Kerwin method is run with a single pass only then the method discussed here again gives better results. Also, the reader may note that the 3-D methods discussed herein were all developed about 30 years ago but in Fuhs' (2005) conclusions it is noted that PUF-2, for most cases, gives adequate results. All of the necessary input to the procedure is easy to understand and is in a form that is familiar to most naval architects. The computational procedure is also easy to understand and economical to use with running times on a computer in the neighborhood of an order of magnitude less than the unsteady lifting surface techniques.

There was a discussion, earlier in this paper, of the possibility of accounting for some of the unsteady effects in this fluctuating force calculation procedure. There has been no proof offered that the unsteady effects are accounted for, but it is important to note that since the comparison with the experimental results has shown satisfactory agreement over a wide range of propeller types and wake conditions, it may be concluded that either the unsteady effects have been accounted for or that they are sufficiently small as to be ignored. While this conclusion is probably valid, in the engineering sense, for the forces transmitted through the propeller shafting, some experimental evidence indicates that this is not true for the individual blade forces.

Author's Note: This paper is a subset of, and was written concurrently with, a NSWCCD Hydromechanics Department report of the same name. Copies of this full report may be obtained by contacting the NSWCCD Technical Information Center.

ACKNOWLEDGEMENTS

The author would like to acknowledge Scott Black for his assistance with using the PUF 2 computer program of MIT and with running this program in the "Expert" mode.

REFERENCES

Boswell, R.J. (December 1967). Measurement, Correlation with Theory and Parametric Investigation of Unsteady Propeller Forces and Moments. Master's Thesis, Pennsylvania State University, Department of Aerospace Engineering.

Boswell, Robert J. & Cox, Geoffrey, G. (January 1974). 'Design and Model Evaluation of a Highly Skewed Propeller for a Cargo Ship'. Marine Technology.

Breslin, J. P. (1970). 'Theoretical and Experimental Techniques for Practical Estimation of Propeller-Induced Vibratory Forces'. Transactions SNAME **78**, pp. 23-40.

Drischler, J. A. (1956). 'Calculation and Compilation of the Unsteady Lift Functions for a Rigid Wing Subjected to Sinusoidal Gusts and to Sinusoidal Sinking Oscillations'. National Advisory Committee for Aeronautics, Technical Note **3748**.

Fuhs, D. (2005). Evaluation of Propeller Unsteady Force Codes for Noncavitating Conditions. Naval Surface Warfare Center Carderock Division (NSWCCD) Report **NSWCCD-50-TR-2005/004**, September.

Jessup, S. D. (1990). Measurement of Multiple Blade Rate Unsteady Propeller Forces. David Taylor Research Center (DTRC) Report **DTRC-90/015**, May.

Von Karman, T. H. & Sears, W.R. (1938). 'Airfoil Theory for Non-Uniform Motion'. Aeronautical Sciences **5**,(10), August.

Kerwin, J. E., & Lee, C. S. (1978). 'Prediction of Steady and Unsteady Marine Propeller Performance by Numerical Lifting-Surface Theory'. SNAME Transactions **86**, pp. 218-253.

McCarthy, J. H. (1961). 'On the Calculation of Thrust and Torque Fluctuations of Propellers in Nonuniform Wake Flow'. David Taylor Model Basin Report **1533**, October.

Tsakonas, S. et al. (1974). 'An Exact Linear Lifting Surface Theory for Marine Propellers in a Nonuniform Flow Field'. Journal of Ship Research **17**(4), pp. 196-207.